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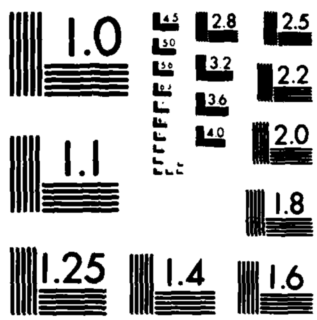
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An Appraisal of the Short-Range Forecast Problem Using Power Spectra

H. STUART MUENCH

19 NOVEMBER 1982

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Recently-published forecast scores were compared, revealing several interesting features. Skill-scores, relative to climatology, for some parameters such as ceiling/visibility and precipitation are much lower than others, such as minimum temperature and pressure gradients. Also, the skill-scores have been improving appreciably faster for forecasts of 36 h (and more) than for forecasts of 24 h (and less). At the shortest ranges, less than 12 h, skill-scores relative to persistence are rather low, with values of 0.0 to 0.5 as typical.

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Power spectra for wind, temperature, dew point, rainfall rate, cloud reflectivity, and extinction coefficient (inversely related to visibility) were computed for periods of 10 min to 20 days, using fall season data from northeast United States. Analyses of these spectra indicate some of the problems in forecasting. Wind, temperature, and dew point spectra all had considerably more power at periods longer than 24 h than did rainfall rate, cloud reflectivity, and extinction coefficient, which relates to differences in forecast skill-scores. The greatest contribution to change for 2- to 8-h forecasts comes from disturbances with periods of about 8 to 32 h. The rainfall-rate spectrum showed large values at short periodicity, but the values are physically consistent with the wind spectrum through a relationship with horizontal convergence.

Discussed in the report are several factors related to the poor performance of the shortest range forecasts. Disturbances with periods shorter than about 24 h are purposely filtered from current operational numerical models, in order to improve performance over longer ranges. The disturbances filtered out may be relatively unimportant to wind and temperature forecasts but quite important for cloud and precipitation forecasts. Disturbances with periods less than about 2 h cannot be adequately resolved temporally or spatially using current weather data, yet these disturbances have sufficient amplitude to contribute noise in the analyses of longer period disturbances. Finally, modern explanations for observed weather patterns in midlatitudes now stress baroclinic instability and wave interaction rather than frontal theory, but we are still lacking in a consistent description of the structure, behavior, and lifetime for mesoscale systems.

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1. INTRODUCTION

Short-range forecasting (0 to 12 h) has long been the "unwanted child" of meteorology. From the development of the Norwegian Frontal Theory to the baroclinic wave theories to the present operational primitive-equation models, the primary emphasis of theory and application has been on forecasts of 24 h and more. Furthermore, the parameters of interest have largely been maximum-minimum temperature and 24-h rainfall, whereas operations exposed to weather problems have serious need for spot forecasts of wind, temperature, humidity, cloud conditions, visibility, and precipitation rate. The developments in operational numerical forecast models have made impressive improvement of forecast skill at ranges of 36 h and more,[1] but this technology improvement does not seem to have impacted on short-range forecast skill. This report will discuss the trends in forecast accuracy and examine power spectra of weather variables to understand better why the present status has evolved. Finally, some fundamental problems of short-range forecasting will be presented.

(Received for publication 19 November 1982)

1. Shuman, G. (1978) Numerical weather prediction, Bull. Am. Meteorol. Soc. 59:5-17.

2. FORECAST SKILL SCORES

Within the past several years, numerous papers in the literature have presented tables and diagrams illustrating forecast "skill" and how the skill has been changing over the years.[2-6] To some, "skill" is defined as the percentage improvement over a forecast of no pressure gradient, whereas to others, "skill" is the percentage improvement over a forecast based on climatological data. Since the latter is a more common reference, we shall use it as a standard and make conversions to climatological base (albeit approximate) when necessary.

Table 1 summarizes data from five of the verification papers, showing the type of forecast, current level of skill (relative to climatology), and the improvement rate. The source papers present diagrams illustrating approximate linear trends in skill with time that could be represented as slopes. A slightly more dramatic presentation is through the computation of time based on th · reaching of perfection at the recent rate of improvement; these values are shown in the column t(100%). Although the levels of skill are not really great (only a few are 50 percent or more) the improvement rates show considerable promise for the future. Looking at the t(100%) values, one notes a curious feature -- that the shortest times (fastest improvement) occur with the longest range forecasts. The last column, t(overtake), indicates how long it would take the longer range forecast to overtake the next forecast at shorter range. Physically, it would seem unlikely that in the future we will see last night's forecast for tonight's weather scoring better than this afternoon's forecast, but this is clearly the tendency in nearly all cases.

The forecast time intervals in Table 1 vary widely among the various forecast parameters, but if one focuses on a particular time period, say about 24 to 36 h, there would appear to be systematic differences in skill with which the parameters are forecast; for example, Figure 1 shows the current skill

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2. Fawcett, E.B. (1977) Current capabilities in prediction at the National Weather Service's National Meteorological Center, Bull. Am. Meteorol. Soc. 58:143-149.
3. Sanders, F. (1979) Trends in skill of daily forecasts of temperature and precipitation, 1966-78, Bull. Am. Meteorol. Soc. 60:763-769.
4. Charba, J.P., and Klein, W.H. (1980) Trends in precipitation forecasting skill in the National Weather Service, Preprints, Eighth Conference on Weather Forecasting and Analysis, Am. Meteorol. Soc., 391-396.
5. German, K., and Hicks, Jr., P. (1981) Air Weather Service ceiling and visibility verification, Bull. Am. Meteorol. Soc. 62:785-789.
6. Zorndorfer, E.A., Bocchieri, J.R., Carter, G.M., Dallaville, J.P., Gilhausen, D.B., Hebenstreit, K.F., and Vercelli, D.J. (1979) Trends in comparative verification scores for guidance and local aviation/public weather forecasts, Mon. Wea. Rev. 107:799-811.

Table 1. Skill-scores and Improvement Rates for Routine Forecasts

Element	Refer-ence	Forecast Time (h)	Current Skill (%)	Improvement Rate t(100%) (yr)	Improvement Rate t(overtake) (yr)
500-mb gradient	1	36	60	32	...
Sea-level pressure gradient	2	36	45	48	...
Minimum temperature	3	18	58	∞	...
Minimum temperature	3	42	38	120	40
Max-min temperature (objective)	2	24	...	21	...
Max-min temperature (objective)	2	48	...	19	18
Quantitative precipitation	3	0-24	50	130	...
Quantitative precipitation	3	24-48	23	90	57
Quantitative precipitation	3	48-72	9	84	62
Probability-of-precipitation	4	3-15	36	307	...
Probability-of-precipitation	4	15-27	27	106	19
Probability-of-precipitation	4	27-39	22	98	50
Ceiling-visibility category	5	3	55	19	...
Ceiling-visibility category	5	6	28	38	∞
Ceiling-visibility category	5	12	10	113	∞
Ceiling-visibility category	5	24	0	84	3

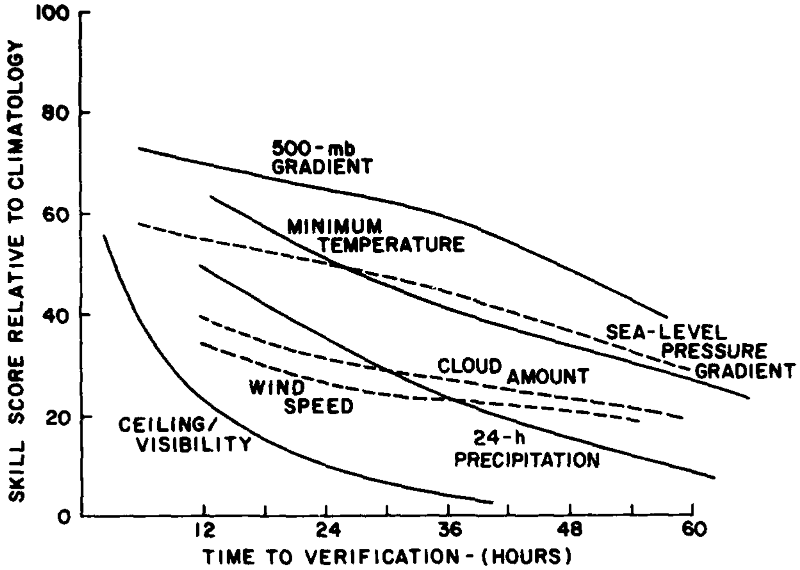

Figure 1. Operational Capability for Routine Forecasts in Mid-latitudes

capabilities for seven different forecast parameters as a function of time interval between last data and verification. Data for Figure 1 came from the same sources as Table 1, supplemented* by data from Zorndorfer et al.[6]

As suspected, there are differences in forecast skill among the parameters, with the highest skill-scores found for the gradients of 500-mb geopotential and sea-level pressure, closely followed by minimum temperature. Distinctly lower are the forecasts for cloud amount, 24-h precipitation and wind speed, and at the very bottom the ceiling-visibility category. For aircraft operations, this is a very unfortunate order. The only consolation is that the trends are towards higher skill-scores for forecast intervals of less than 12 h. However, the initial condition is normally available for these forecasts, and a forecast of no change with time or "persistence" would score quite well with respect to climatology for periods less than 12 h. Thus a more realistic reference or control for short-range forecast skill-scores would be persistence.

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*Reference 6 was used for wind speed skill and for ceiling/visibility skill longer than 12 h. Reference 5 was used for ceiling/visibility for 3 to 12 h, but since the scores were based on categories other than probability, they did not represent the full skill available for longer range forecasts when small but meaningful probabilities can be forecast for many categories.

Table 1 Skill-scores for Short-range Forecasts

Element	Ref.	Form	Type	Mode	No.	Time (h)	Skill-Score Pers.	Skill-Score SSG	No.	Time (h)	Skill-Score Pers.	Skill-Score SSG
Cloud Amount	7	Prob.	Subj.	Routine	250	1-4	0.2	.1				
Cloud Amount	8	Prob.	Subj.	10 Cases	1800	1-4	0.46	...				
Cloud Amount	9	Categ.	Obj.	12 Cases	1500	2	0.0	...	1500	4	0.17	...
Surface Wind	7	Vector	Subj.	Routine	250	1-4	0.0	...				
Surface Wind	8	Vector	Subj.	10 Cases	1800	1-4	0.10	...				
Visibility (Extinction Coefficient)	7	Prob.	Subj.	94 Cases	3000	1/2	0.35	0.14	1500	1	0.40	0.16
Ceiling-Visibility	5	Categ.	Subj.	Routine	140000	3	0.44	...	142000	6	0.38	...
Rainfall	9	Prob.	Obj.	12 Cases	1500	2-3	0.00	...	1500	4-5	0.30	...
Rainfall	8	Prob.	Subj.	10 Cases	600	3-9	0.46	...				

Form
Prob.: Probability
Cate.: Category

Type
Subj.: Subjective
Obj.: Objective

Skill-score Reference
Pers.: Persistence
SSG: Single-station-guidance (stochastic model or climatology-persistence tables)

7. Muench, H.S., and Chisholm, D.A. (1981) An assessment of mesoscale forecast experiments, Proc. IAMAP Symposium, Hamburg, 25-28 August 1981, 363-367.

8. Chisholm, D.A., Jackson, A.J., Niedzielski, M.E., Schecter, R., and Ivaldi, C.F. (1982) The Use of Interactive Graphics Processing in Short-range Terminal Weather Forecasting: An Initial Assessment, AFGL-TR-(in preparation).

9. Muench, H.S. (1981) Short-Range Forecasting of Cloudiness and Precipitation Through Extrapolation of GOES Imagery, AFGL-TR-81-0218, AD A108678.

Table 2 summarizes some skill-scores for short-range forecasts made experimentally and operationally. The skill-scores with respect to persistence range from 0 to less than 50 percent, meaning that less than 50 percent of the changes in weather over a few hours are being correctly forecast. When compared to scores of a statistical routine using both persistence and climatology (SSG), the improvement is considerably less.

There are three puzzling questions suggested by the verification data: (1) Why are short-range forecasts so poor in forecasting change when the changes are so imminent? (2) Why are forecasts of operationally important variables such as wind, cloud, and visibility so much lower in skill than pressure gradient? (3) Why are the longer-range forecasts improving more rapidly than shorter-range forecasts?

3. DIAGNOSING WITH POWER SPECTRA

A useful approach to analyzing forecast problems is to examine the power spectra of the elements in question. The power spectrum of a quantity presents the power or square-of-amplitude as a function of time frequency; it can show the contribution to the time variance of a quantity due to disturbances with frequencies varying over orders of magnitude. Spectra of temperature and wind have been computed[10, 11, 12] for frequencies corresponding to periods ranging from seconds to years. These spectra for mid-latitudes reveal sharp peaks corresponding to annual and diurnal cycles; they show more rounded peaks at about 3 to 6 days owing to baroclinic waves (cyclones and anticyclones) and at about 1 to 2 min due to boundary layer turbulence. The amplitudes indicate the importance to the forecast problem; the frequency or period is an important clue to the physical forcing and an indication of the type of solution to be sought. With quantitative spectral data, we can compute the contribution to change over the time intervals corresponding to short-range forecasts, due to particular parts of the spectrum such as the traveling cyclones, the diurnal changes, and the turbulence range. Such a diagnosis would indicate where the emphasis should be in data analysis and to what extent temporal (or spatial) smoothing of raw data might be needed.

---

10. Oort, A.H., and Taylor, A. (1969) On the kinetic energy spectrum near the ground, Mon. Wea. Rev. 97:623-626.

11. Vinnichenko, N.K. (1970) The kinetic energy spectrum in the free atmosphere - 1 second to 5 years, Tellus 22:158-166.

12. Smedman-Högström, A-S, and Högström, U. (1975) Spectral gap in surface layer measurements, J. Atmos. Sci. 32:340-350.

To the extent that the periodicities portrayed in a spectrum recur regularly, for example, annual, diurnal, and cyclone cycles, the amplitudes are representative of "typical" disturbances. However, in the case of rare events such as hurricanes or severe storms, often of short duration, the power spectrum may seem deceptively weak at the appropriate frequency, leading to an underestimate of a forecast problem. This point will be discussed in more detail in Section 7.

There are also some more theoretical interpretations that can be made from spectra of the forecast variables. The classical frontal wave models (baroclinic waves) depict simple cloud, precipitation, and visibility patterns propagating and evolving together with the surface wind and temperature patterns. Thus we would expect the spectra of all these variables to appear similar. Theoretical studies of baroclinic instability predict that energy will cascade from the most unstable disturbances to smaller and higher frequency disturbances.[13, 14] This concept is important to mesoscale forecasting since it implies that a numerical model of high resolution and ability to forecast baroclinic development should be capable of correctly forecasting the smaller-scale fronts and troughs and their attendant weather patterns. Other scientists[15] note that the boundary layer turbulence peaking at about 1-km size and 2-min frequency can generate larger and longer period disturbances (in an unpredictable manner) and could affect mesoscale and perhaps larger disturbances. These theories predict distinct and separate variations of power with changing frequency, probably identified in the spectra.

4. DATA SOURCES FOR POWER SPECTRA

For the purposes of this report, we shall consider short-range forecasts as predictions of "instantaneous" values at a "point", and focus on weather conditions 2 to 8 h after the most recent weather data. By "instantaneous" we shall assume a 5-min mean value. While higher frequency phenomena certainly cause problems, forecasters and users cannot respond to a faster forecast-observation cycle; they acknowledge occurrence of high-frequency changes by terms such as "gusts" and "briefly--" without specifying a particular time. If we are to be consistent with our 5-min definition for "instantaneous", our "point" should refer to an area of the size 5 min times a typical motion speed, say 10 m/sec, or 3 km--the length of a good sized runway. To define the other end of the time scale of interest, we

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13. Charney, J.G. (1971) Geostrophic turbulence, J. Atmos. Sci. 28:1087-1095.
14. Blumen, W. (1978) Uniform potential vorticity flow: part 1. theory of wave interactions and two-dimensional turbulence, J. Atmos. Sci. 35:774-783.
15. Gage, K.S. (1979) Evidence of a $k^{-5/3}$ law inertial range in mesoscale two-dimensional turbulence, J. Atmos. Sci. 36:1950-1954.

assumed that periodicities greater than 20 days would be too low in amplitude to have a significant effect on changes over a period of 0 to 8 h (which proved quite correct), and so 20 days was chosen as the fundamental cycle in these calculations.

To obtain a useful power spectrum, one needs a long period, with frequent observations, and preferably no gaps and no errors. During a mesoscale forecast experiment by Hering et al,[16] observations were taken from as many as 26 remote sites, transmitted over land lines, and archived on magnetic tape, in addition to use in the real-time experiments. The forecast experiments, which ran from 1972 to 1976, have been completed,[7] but because there are still uses for the basic data, the data of the first year have been recently edited and 1-min mean values of wind direction, speed, temperature, dew point, and extinction coefficient (inversely related to visibility) placed on tape. A 75-day period from the fall of 1972 was selected for computations of power spectra, as the period contained a variety of weather conditions. A station near the west end of the primary runway at Hanscom Air Force Base, Bedford, Mass.,(station WRY) was chosen as a representative site, with sensors located about 3 to 4 m above a grass-covered area.

A power spectrum routine (formerly used in solar-weather studies[17]) was adapted to input/output requirements for the present studies. A preliminary routine converted data to 5-min means, and then two passes were made with the power spectrum program. First, data extracted at 1-h intervals were used to compute lag covariances from zero to 240 h in 1-h steps[18] and then to compute the power spectrum (Hanning smoothing) for 2 to 480 h. In the next pass, all 5-min data were used to compute the spectrum from 10 min to 72 h. The first spectrum was used for periodicities from 20 days to 6 h (discarding 2 to 6 h data to avoid aliasing problems), and the second spectrum for periodicities of 6 h to 10 min.

While the basic data were quite satisfactory for the mesonet forecast experiments, by the time editing was completed, up to 25 percent of some of the sensor data were missing for station WRY. Missing periods ranged from an hour or two to several days, due to a variety of problems from instrument failures, to computer problems to data transmission noise. Since these gaps were not due to meteorological factors, they might make the spectra a little "noisy" in appearance but should not affect the over-all characteristics.

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16. Hering, H.S., Muench, H.S., and Brown, H.A. (1972) Mesoscale forecasting experiments, Bull. Am. Meteorol. Soc. 53:1180-1183.

17. Shapiro, R., and Ward, F. (1962) A neglected cycle in sunspot numbers? J. Atmos. Sci. 19:506-508.

18. Panofsky, H.S., and Brier, G.W. (1963) Some Applications of Statistics to Meteorology, The Penn. State University, University, PA (p.b. 140-147).

Another AFGL data-gathering experiment has more recently been under way; this one at Otis Air Force Base, on Cape Cod (Falmouth, Mass.). At this site the sensor data archived include tipping-bucket rain-gauges and radiometers. By using the total "counts" archived at 10-min intervals from 2 rain-gauges, we can get 10-min rainfall rates with a sensitivity of 0.03 in. per hour. While this sensitivity is a bit crude for light rains, it is adequate for the heavier rains, which account for most of the annual rainfall accumulation and is of greatest interest to the forecaster. A 100-day period from September 1981 to mid-December 1981 was used for the power-spectrum of rainfall rate, including a variety of conditions, from thunderstorms to major coastal cyclones. While spectra for wind, temperature, dew point, and extinction coefficient were computed for periodicities down to 10 min, the minimum rainfall-rate periodicity was 20 min.

In 1981, NOAA-NESS gave AFGL permission to conduct five "rapid-scan" experiments using the GOES East satellite, in order to study the development of mesoscale features associated with developing cold season cyclones. During these experiments, satellite scans of mid-latitudes were made at 7-1/2-min intervals over a 3-h period in the afternoon. A time series of 25 consecutive satellite measurements is not very long for determining spectra, but this sample represents a rather unique opportunity to study short-term variability over widespread areas. The AFGL McIDAS system collected imagery for the IR channel with 4-mile resolution (7 km) and the visible channel with 1-mile (1.8 km) resolution. The visible channel data were corrected for the secant of the solar zenith angle and later given a finer correction based on time series over clear ground and stable orographic clouds (as determined by IR values). The basic navigation was refined by references to known landmarks. Infrared values were converted to equivalent blackbody temperatures. The imagery data were interpolated and smoothed to a latitude-longitude grid with 6 nm (11 km) resolutions and values extracted at 1/2 degree (staggered) intervals, providing 110 different times series. Lag covariances were then computed, summed over the 110 locations and from the totaled covariance, spectra were computed from 15 min to 3 h.

The spectrum for visible reflectivity was complemented by data from two other sources: (1) the solar radiometer measurements archived at Otis Air Force Base; and (2) a 30-day sample of hourly weather reports. The first was used to estimate reflectivity by essentially assuming that light not measured at the ground was scattered out to space, and values were used to compute an estimated reflectivity spectrum from 8 min to 8 h. In order to extend the spectrum to still lower frequencies, relations used by Muench[9] to estimate cloud amount, cloud layers, and precipitation rate from satellite measurements were inverted to produce an algorithm for estimating reflectivity based on aviation hourly reports.

Reports from Burlington, Vt.; Boston, Mass.; and Washington, D.C., during November 1977 were then converted to reflectivity and the spectrum computed from 6 h to 20 days.

5. SPECTRA OF SEVEN WEATHER PARAMETERS

There are several popular forms for presenting power spectra. In our case, we have periodicities ranging from minutes to days, three orders of magnitude, and thus the need for a logarithmic frequency scale. As pointed out by Zangvil,[19] if power-times-frequency is plotted against the logarithm of frequency, the area under the curve is proportional to the variance, and one can visually compare the relative contribution to total variance from various parts of the spectrum. This form of presentation will be used first in discussing implications of the spectra to forecast problems. On the other hand, theoretical questions involve slopes that are based on log-log plots; this form will be used in discussing why the spectra are as observed.

The computed spectra for wind, temperature, dew point, cloud reflectivity, extinction coefficient, and rainfall rate are shown in Figures 2a through 2e. The spectra for wind and temperature look very much like previously published spectra,[10, 12, 20] illustrated by the smooth wind speed spectrum derived from Figure 10 of Smedman-Högström and Högström.[12] Even though our sampling period is not long, the features seem to be typical of mid-latitudes, especially the cooler seasons. A closer inspection suggests that the frequency for the wind vector peak is higher (2-1/2 days versus 3 days) compared to Oort and Taylor's[10] spectra for Caribou, Maine, which is perhaps a result of the smaller sample for this study. The minima at 80 h (3.33 days) for temperature and dew point are also likely due, at least in part, to small sample. With respect to the forecast problem for wind, temperature, and dew point, the major features are: (1) the large amount of power in the spectrum from 2 to about 8 days, primarily owing to traveling baroclinic waves; and (2) the diurnal and semidiurnal "spikes". For periodicities shorter than about 8 h there is little power, implying few problems to a forecaster, at least on a routine basis.

With so much power in the low frequencies for wind and temperature, it is clear why the major emphasis has been centered on techniques to forecast the baroclinic cyclones. A perennial problem with numerical models in forecasting

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19. Zangvil, A. (1977) On the presentation and interpretation of spectra of large-scale disturbances, Mon. Wea. Rev. 105:1469-1472.

20. Harrington, J.B., and Heddinghaus, T.R. (1974) Determinism in mesoscale wind spectra at Columbia, Missouri, J. Atmos. Sci. 31:727-737.

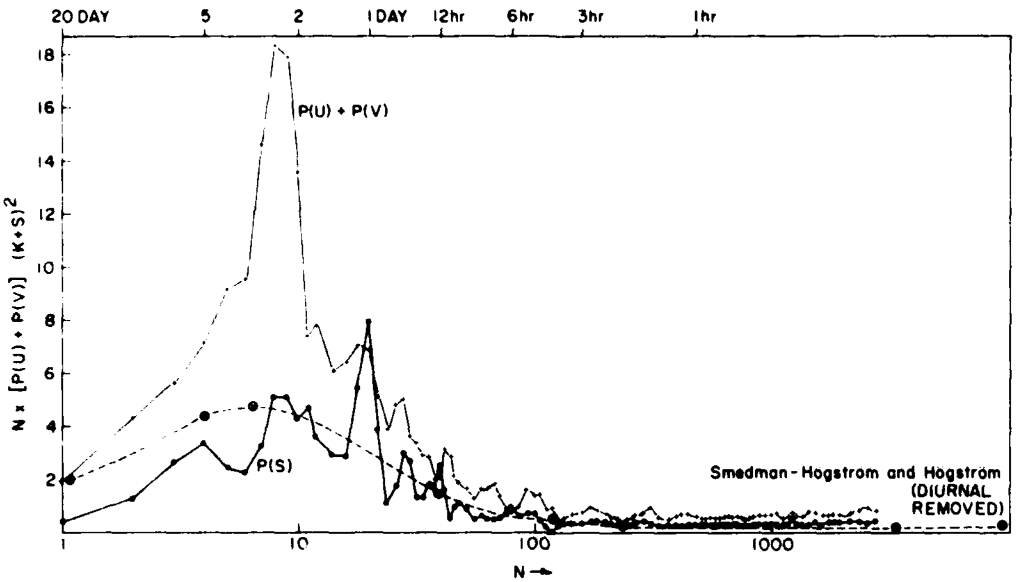

Figure 2a. Power Spectra for Wind Vector - [P(U) + P(V)] and Wind Speed - P(S)

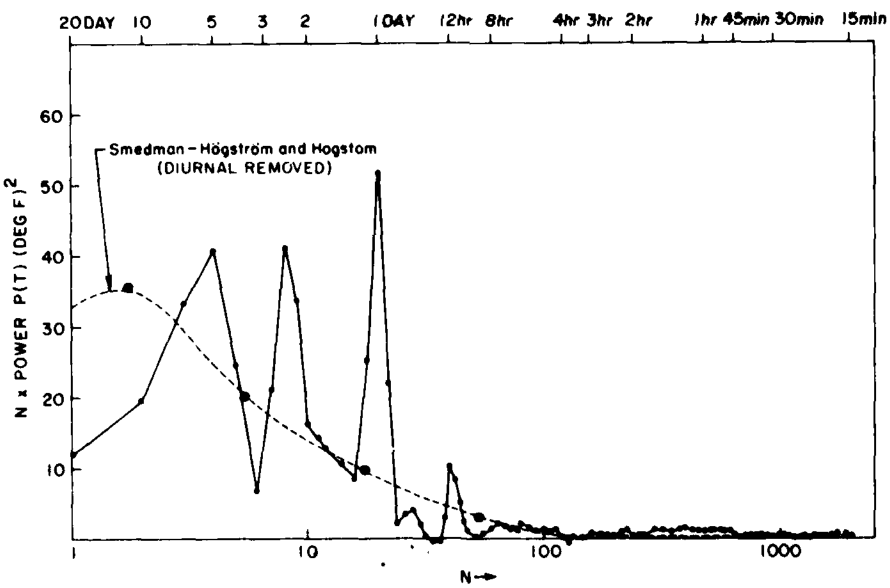

Figure 2b. Power Spectrum for Temperature - P(T)

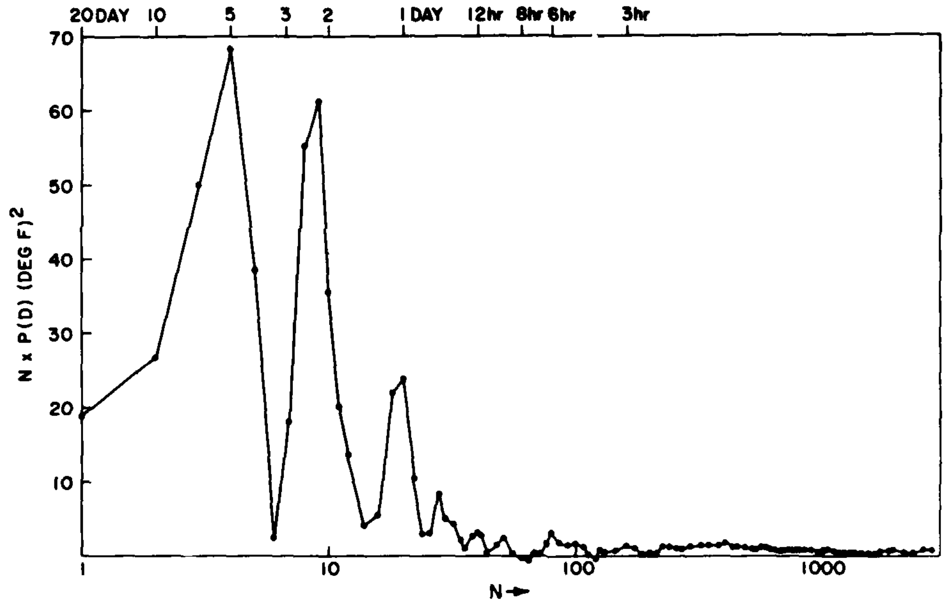

Figure 2c. Power Spectrum for Dew Point - P(D)

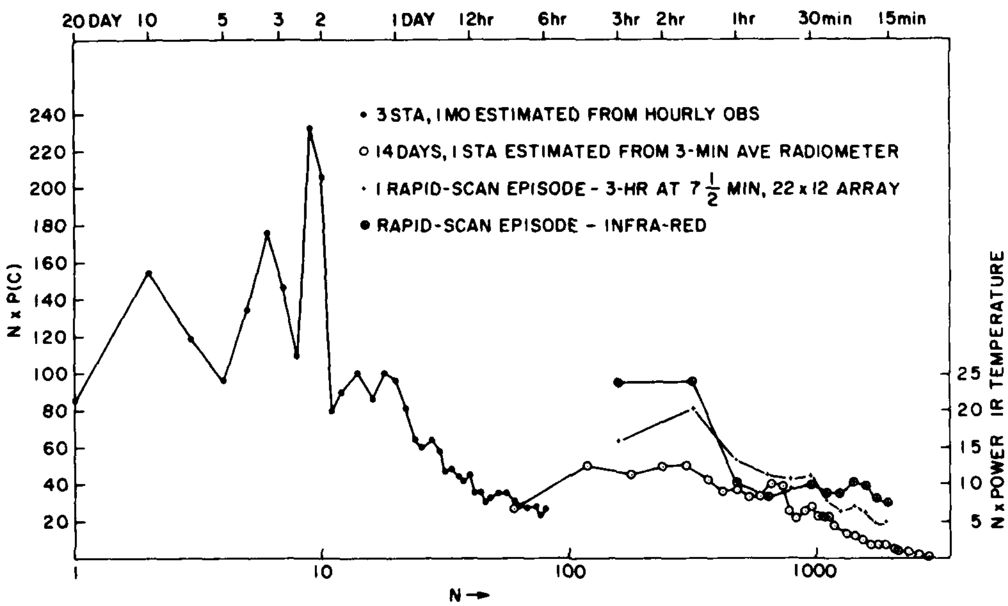

Figure 2d. Power Spectrum for Cloud Reflectivity - P(C)

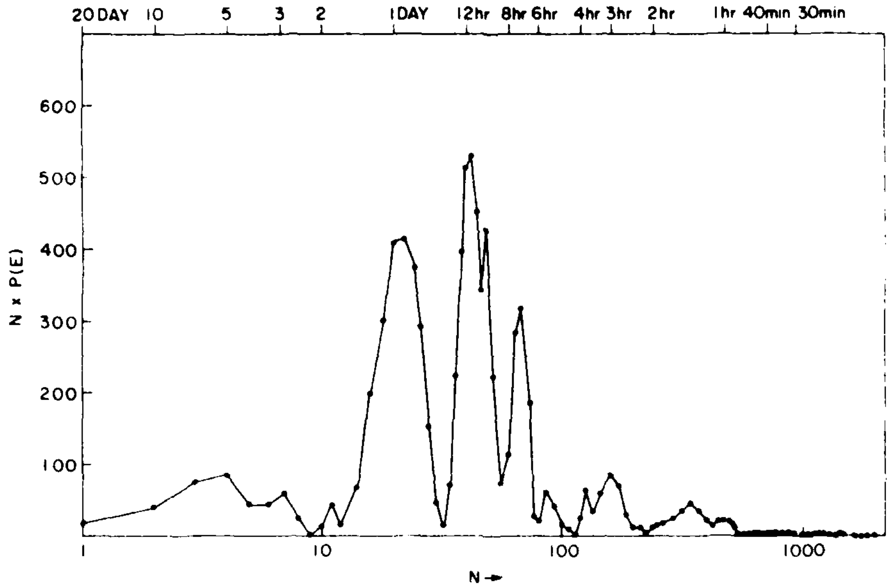

Figure 2e. Power Spectrum for Extinction Coefficient - P(E)

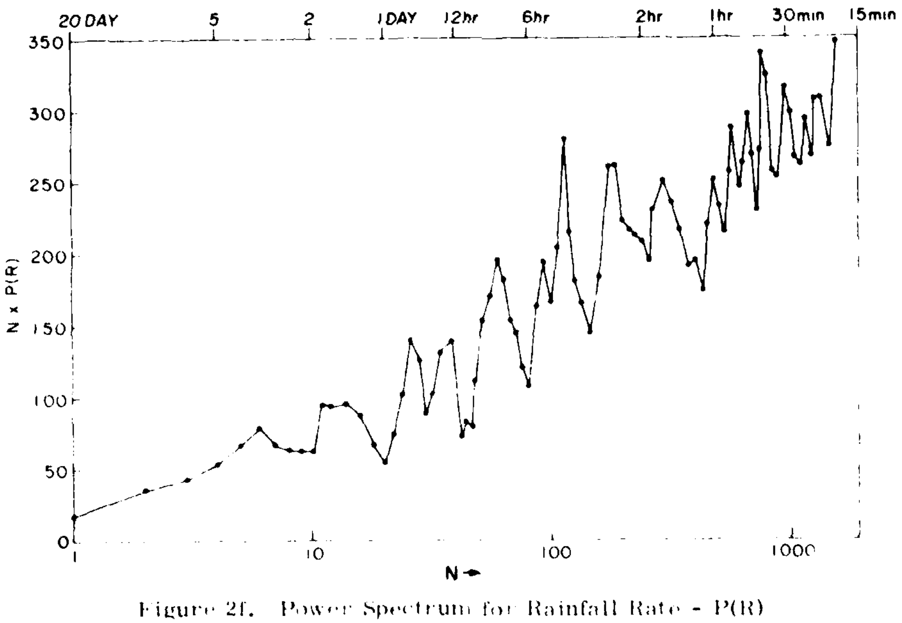

Figure 2f. Power Spectrum for Rainfall Rate - P(R)

these cyclones is that "noise" in the initial data will at times grow into unrealistic disturbances. A major improvement in the models is the initialization schemes that damp out the noise so that the forecasts are now realistic to beyond 48 h. However, in damping the noise, for the most part, the models remove disturbances with periodicities of less than about 24 h. Thus, the models simply cannot forecast some of the variance, which is percentage-wise more important to the shorter-range forecasts; this explains why skill for longer-range forecasts is improving faster than shorter-range forecasts.

Looking further through the spectra--cloud reflectivity, extinction coefficient, and rainfall rate, we note that all have spectra different from those of wind and temperature. In the case of cloud reflectivity, there is a modest shift of variance to periods less than 24 h, while in extinction coefficient spectra nearly all the power is in 6- to 36-h periodicities. This is consistent with the prominent role the diurnal heating cycle has on visibility (and low ceiling) climatology. The rainfall rate power increases right out to the limit of resolution at 20 min, and one wonders where it peaks. The differences between these spectra are further highlighted in Table 3, where the total variance is broken up percentage-wise for six different frequency bands. We can note that the two lowest frequency bands account for 79 percent of the temperature variance, and 66, 57, and 18 percent of the variances for cloud reflectivity, wind speed, and extinction coefficient, respectively. If we glance back to Figure 1, we see that this is the very same order for the skill-scores of comparable forecast parameters. One reason that the parameters with variance at long periodicity are more skillfully forecast is that the numerical guidance forecasts have filtered out the high-frequency changes. Another reason is related to the size of the patterns (assuming the changes are due to moving patterns) and the effects of displacement errors. For example, a typical extrapolation error is about 15 percent of the displacement, which leads to forecasts that are 90 degrees out of phase, and of little value when the pattern has moved about 1-1/2 cycles. These two factors, no doubt, account for the vanishing skill-score for ceiling/visibility beyond 24 h, as seen in Figure 1.

The bottom row in Table 3 shows the ratio of wind speed power to wind vector power, averaged over the six frequency bands. Oort and Taylor[10] noted that the diurnal and semidiurnal periodicities are more pronounced for wind speed than for wind vector components because the diurnal changes in boundary layer near the ground primarily affect the speed and not direction. Thus, in Table 3 we see a ratio of 0.62 for the 8- to 32-h period, the highest of all the six bands, and in Figure 2a, power for the diurnal and semidiurnal spikes exceed the combined power for the u and v components (the vector wind power). If we have a field of horizontal whirls, like cyclones and anticyclones, the variance of each component is appreciably greater than the variance for speed, because the components vary

Table 3. Distribution of Power of Forecast Elements Among Frequency Bands

(Fall Season, New England)

Element	Baroclinic Cyclones "Slow" (20 Days – 5 Days)	Baroclinic Cyclones "Fast" (5 Days – 32 h)	Tides, "Fronts" (32 h – 8 h)	Mesoscale Disturbances "Slow" (8 h – 2 h)	Mesoscale Disturbances "Medium" (2 h – 32 min)	Mesoscale Disturbances "Fast" (32 min – 8 min)
Temperature - P(T) 5-min mean	0.41	0.38	0.17	0.02	0.02	0.01
Dew point - P(D) 5-min mean	0.48	0.40	0.08	0.02	0.02	0.01
Wind vector P(U) + P(V) 5-min mean	0.20	0.51	0.19	0.05	0.03	0.03
Wind speed P(S) 5-min mean	0.14	0.43	0.30	0.05	0.04	0.04
Cloud reflectivity P(C) ~5-min mean	0.31	0.35	0.16	0.08	0.07	0.02
Extinction coefficient P(E) 5-min mean	0.10	0.08	0.59	0.17	0.06	0.01
Rainfall rate P(R) 10-min mean	0.04	0.14	0.07	0.22	0.27	0.25
Wind ratio P(S) / [P(U) + P(V)]	0.29	0.35	0.62	0.47	0.52	0.50

on either side of zero and the speed is never negative. Thus, the wind vector power due to traveling quasi-horizontal disturbances should be more than twice the wind speed power, which we clearly see in the last line of Table 3 for periodicities longer than 32 h (1-1/4 days). In Figure 2a, the ratio at the spectral peak of 2-1/2 days is about 4 to 1. At periodicities shorter than 8 h, Table 3 shows ratios near 0.50, which would be consistent with what one would expect from isotropic, three-dimensional turbulence.

To understand better the short-range forecast problem, we need to see the contribution of the bands in the spectra to changes over short time periods; in other words, persistence errors. If the initial data are at time zero and we want to know the mean-squared change to all times between t_1 and t_2 (2 and 8 h in our case) due to disturbances of frequency f and power $P_f(x)$ for parameter x, then we use:

$$\overline{\Delta x^2} = P_f \left[1 - \frac{1}{2\pi f(t_2 - t_1)} \left(\sin(2\pi f t_2) - \sin(2\pi f t_1)\right)\right] \quad . \tag{1}$$

The expression in brackets represents a weighting function for the mean-square change; an example is shown in Figure 3. One can see that periodicities less than 6 h contribute fully to the change over 2 to 8 h and periodicities from 6 to 18 h contribute more than full power. In the latter case, most of the time, the time zero state is the low (high) part of the cycle and the final state is the high (low) part. At frequencies less than an 18-h periodicity, the weighting drops off, approaching zero by 20 days. If all periodicities were equal in amplitude, Figure 3 indicates that only periodicities less than about 18 h would be important in short-range forecasting. However, Figures 2a through 2e indicate all periodicities are not equal and integration of Eq. (1) over the six bandwidths produced the data for Table 4. Overall, the table indicates that, except for rainfall rate, we should concentrate on the disturbances that cause periodicities of 8 to 32 h, which contribute most strongly to the change over the 2- to 8-h period. Also, except for rainfall rate, the contribution from periodicities less than 2 h is small but not negligible; it creates problems. First, the frequencies are too high (and scale size likely too small) to be forecast from hourly airway observations or even current satellite or digitized radar data. Even if properly defined, small errors in phase speed or development would extrapolate into unacceptable errors as one pushed out to 8 h. Since they cannot be forecast, these disturbances become noise and a further problem because they degrade the analyses of lower frequency disturbances. Thus, mesoscale forecasters also have an initialization problem, one which has really not yet been addressed.

Table 4. Contribution to the Variance of Change, From Time Zero to the 2-8 h Period (2-8 h persistence error) From Power Spectra Bands

Element/RMS Change		20 Days	5 Days	32 h	8 h	2 h	32 min	8 min
Temperature ± 4.5F	5-min mean	0.03	0.23	0.55	0.08	0.07	0.04	
Dew point ± 4.1F	5-min mean	0.05	0.33	0.43	0.06	0.08	0.04	
Wind vector ± 3.4 knots	5-min mean	0.02	0.23	0.49	0.11	0.08	0.07	
Wind speed ± 2.5 knots	5-min mean	0.01	0.16	0.55	0.11	0.07	0.10	
Extinction coefficient ± 24.4 × $10^{-4}m^{-1}$	5-min mean	0.00	0.03	0.71	0.19	0.06	0.01	
Cloud reflectivity ± 0.14	~5-min mean	0.01	0.17	0.38	0.21	0.18	0.05	
Rainfall rate ± 3.1	10-min mean	0.00	0.02	0.16	0.24	0.29	0.30	

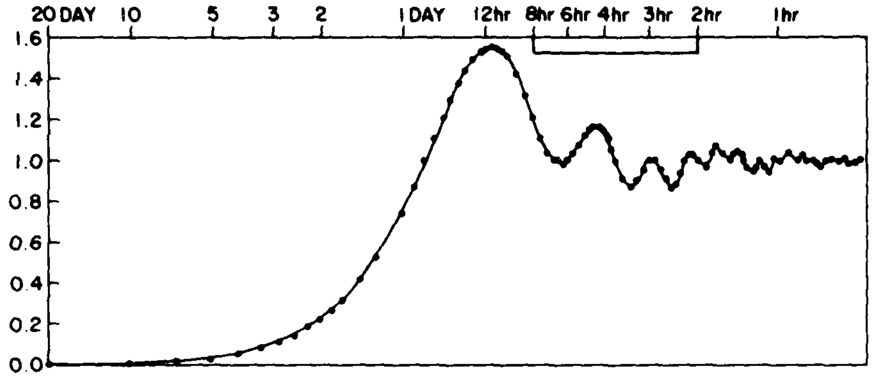

Figure 3. Contribution to Change From Initial Condition for All Forecasts of 2 to 8 Hours From Initial

6. REASONS BEHIND THE OBSERVED SPECTRA

Beginning with a paper by Charney[21] in 1947, meteorologists have shown that given a rotating earth with the observed large-scale temperature gradients, quasi-horizontal disturbances with a scale size of about 3000 to 4000 km will intensify exponentially. These theories of baroclinic instability correctly predict the observed structure of intensifying surface cyclone-anticyclone systems and accompanying upper-level trough-ridge systems, and also predict eastward propagation at 10 to 20 m/sec (20 to 40 knots). This propagation results in local periodicities of about 3 days in wind and temperature as shown in Figures 2a and 2b. However, the basic theory would predict the formation of simple, symmetric disturbances; yet we typically observe more complicated troughs and ridges on the surface pressure map, and still more complex patterns in satellite images and radar composites. Baroclinic theory predicts that such small-scale features should be stable and decay. Why do they exist?

If there were only one cyclone and anticyclone on earth at a time, they might very well be symmetric, but normally there are many baroclinic disturbances of varying size, as well as orographically forced disturbances. Current theory[13,14] suggests that disturbances of different sizes interact ("nonlinear interaction"), leading to the development of both larger and smaller size disturbances, which further interact, and so on. This interaction theory predicts that the power for wind and temperature disturbances smaller than wavenumber 8 (3000 km at 50 N)

21. Charney, J.G. (1947) The dynamics of long waves in a baroclinic westerly current, J. Meteorol. 4:135-162.

will decrease as the cube (or -3 power) of the wavenumber. Studies of the power-versus-wavenumber for wind and temperature[22, 23] based on radiosonde data indicate a slope of about -2.1 to -2.7 for levels of 850- to 200-mb, down to the resolution limit of about 1200 km. A study based on satellite microwave measurements of temperatures near the 200-mb level[24] indicates a slope of near -3.1 for disturbances from about 2000 to 500 km in size. If these disturbances propagate with the larger baroclinic waves, then we should see slopes of -2.1 to -3.1 in the time series spectra of wind and temperature from about 2-day frequency to at least 10-h frequency. In Figures 4a and 4b we see that when the data for our station WRY are plotted on log-log diagrams,* there is a slope of a little less than -3 for this portion of the spectra. Similar slopes for this spectral range have also been reported using time series of 75-m winds.[25]

Actually, the correspondence between the slopes for space and time spectra of wind and temperature may be somewhat fortuitous. Willson[26] separated fields of geopotential and temperature at 500- and 300-mb levels into propagating and stationary patterns and allowed the stationary patterns to vary in amplitude with time. Perhaps not a coincidence, the power of stationary pattern oscillations of all scales from 24,000 to 2000 km decayed at about a -3 power for periods between 3 days and 1 day. This means that just because we see a -3 power slope on log-log diagrams, we cannot assume it is due to the interactions of traveling waves; it might involve oscillations in time from stationary patterns. For example, it is easy to imagine that the flow over even small-scale terrain would be affected by a traveling wave and that the terrain-induced disturbances would oscillate with a frequency determined by the size and speed of the traveling disturbance, as well as relationship to the amplitude.

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*Before plotting the data on log-log diagrams, the diurnal periodicities were removed by subtracting out the mean values for each GMT hour from the values and recomputing the spectra. The log of frequency-times-power is plotted against log of frequency for easier viewing, but line labeled -3 represents a true -3 slope for log of power versus log of frequency.

22. Julian, P.W., Washington, L.H., and Ridley, C. (1970) On the spectral distribution of large-scale atmospheric kinetic energy, J. Atmos. Sci. **27**:376-387.

23. Julian, P.W., and Cline, A.K. (1974) The direct estimation of wavenumber spatial spectra of atmospheric variables, J. Atmos. Sci. **31**:1526-1539.

24. Stanford, J.L. (1980) Global brightness temperature at high wavenumbers utilizing satellite microwave measurements, J. Atmos. Sci. **37**:1070-1076.

25. Hess, G.D., and Clarke, R.H. (1973) Time spectra and cross spectra of kinetic energy in the planetary boundary layer, Quart. J. Meteorol. Soc. **99**:130-153.

26. Willson, M.A.G. (1975) A wavenumber-frequency analysis of large-scale tropospheric motions in the extratropical northern hemisphere, J. Atmos. Sci. **32**:478-488.

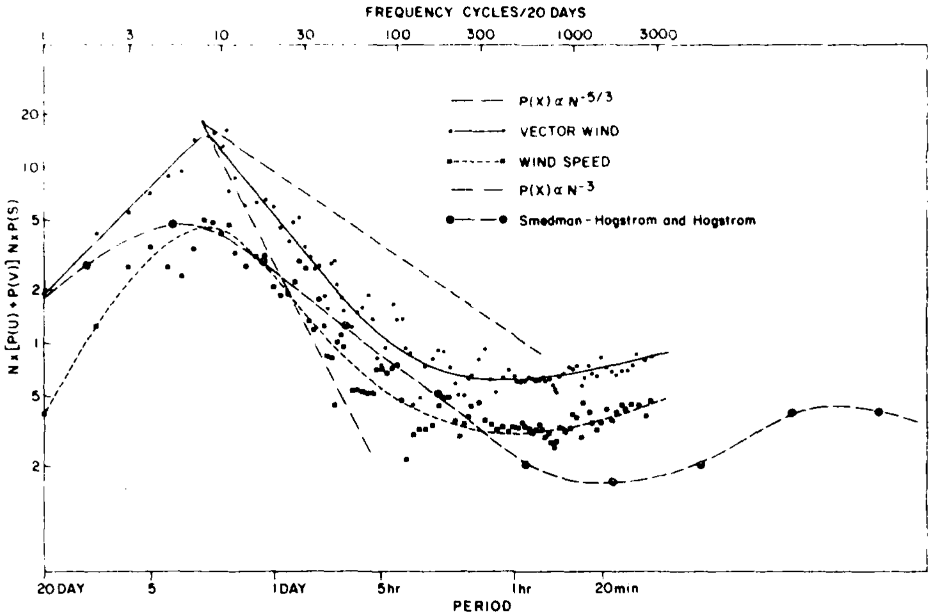

Figure 4a. Power Spectra (log-log) Wind Vector and Wind Speed

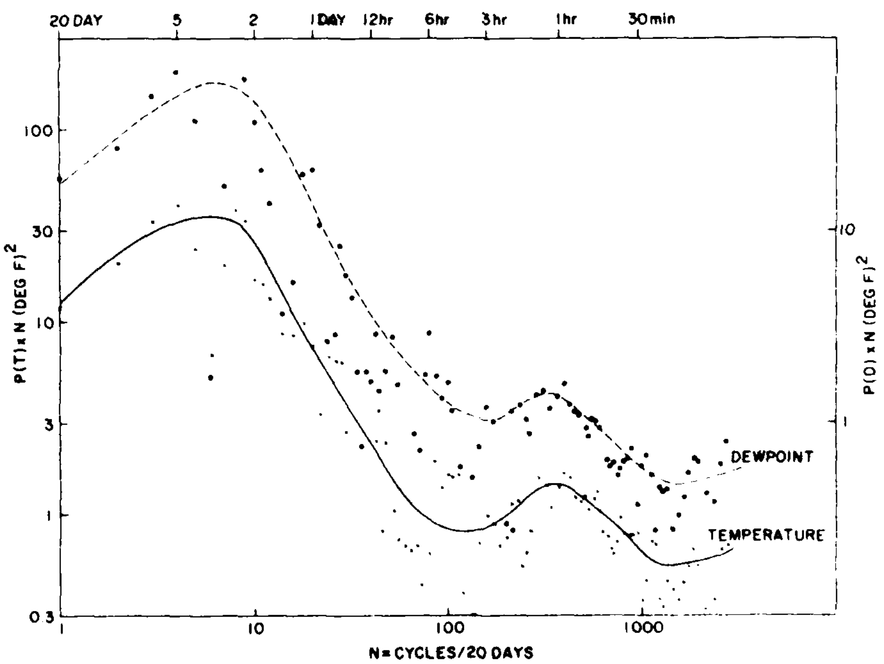

Figure 4b. Power Spectra (log-log) Temperature and Dew Point

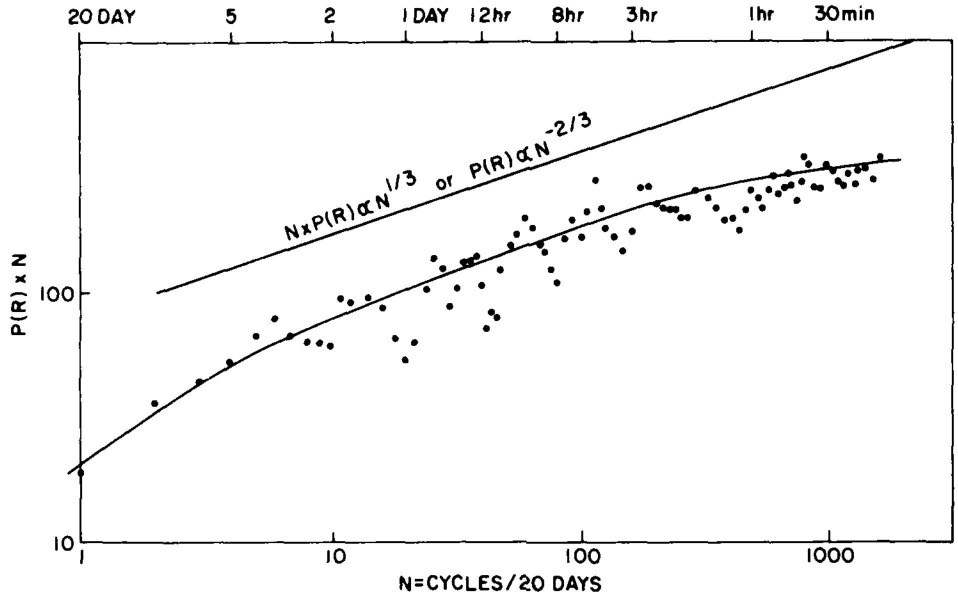

Figure 4c. Power Spectra (log-log) Rainfall Rate

At the high-frequency end of the spectrum there is another source of energy for atmospheric disturbances, well known to meteorologists; this source is related to vertical wind shear and vertical temperature gradient. Under conditions of strong vertical shear and/or low level heating, eddies will develop with typical scales of about 1 to 3 km. On occasion, such conditions occur in the free atmosphere above 1500 m, resulting in clear-air turbulence. Much more frequently, these conditions occur in the lowest 1500 m of the atmosphere, producing boundary layer turbulence. The peak for the power spectrum in boundary layer turbulence is at periodicities of about 1 to 2 min.[12] At higher frequencies, the spectrum has been well described in theory and observation by a -5/3 power law with the log of power decreasing with the log of frequency. Unfortunately, there are presently no rigorous theories for the behavior of the spectrum for periodicities longer than a few minutes. The wind spectra presented by Smedman-Högström and Högström[12] and by Harrington and Heddinghaus,[20] (also Figure 4a) all suggest that at least at the surface the disturbances related to cyclone-scale interactions cease to be dominant at periodicities less than about 6 h, and some other disturbances dominate the spectrum from 6 h to the periods when classical boundary layer turbulence prevails. In lieu of theory, there is speculation (for example, Harrington and Heddinghaus[20] and Fiedler and Panofsky[27]) that this intermediate range turbulence could be due to sea-breezes, squall-lines, mesoscale-complexes, roll-vortices, gravity-waves, and other mesoscale disturbances. Gage[15] suggests there may be "two-dimensional reverse-cascading energy" with some boundary-layer turbulent energy cascading to larger scales (longer periodicities) than the primary turbulent eddies. If the wind disturbances in this intermediate range from periodicities of about 10 min to 6 h are directly related to boundary layer turbulence, as would seem likely, these disturbances would be predictable only in a statistical sense, providing a probability of occurrence but not a specific time of occurrence.

In Figure 4b (and less obviously in Figure 2b) there are peculiar "bumps" in the spectra for temperature and dew point, peaking at about 1.3 h or 80 min, which do not appear in other reported spectra such as Smedman-Hogstrom and Hogstrom.[12] Speculating on the spatial spectrum of scales shorter than 1200 km, Charney[13] suggested... "At still higher wavenumbers one might expect genuine frontal discontinuities to produce a k^{-2} dependence...," and that these peaks occur both in temperature and dew point might suggest a preferred time scale for sharp surface fronts. A survey of large temperature changes over 45-min periods in the WRY data sample indicated that many of the cases were indeed cold or warm frontal passages with temperature changes of about 4 to 6 degrees in 20 to 30 min, and a pronounced wind shift (usually clockwise) and a vector magnitude change of about 5 knots (2-3 m). The cold front has very rapid wind shifts, so the power would appear at much higher frequencies. The wind shifts for the warm frontal passages were more gradual, but the shifts were not much larger than seen in nonfrontal disturbances that occur more often, and thus the fronts are lost in the "noise" of the wind spectrum.

At first glance, there would appear to be no relationship between the wind spectrum in Figure 4a and the rainfall-rate spectrum of Figure 4c. In the latter case, there does seem to be a consistent slope through the scatter of points that deserves an explanation. For the portion from 3 days to 30 min (limit of resolution) the slope would indicate $f \cdot P(R) \propto f^{1/3}$ or $P(R) \propto f^{-2/3}$. The section of the power spectrum for vector wind from 48 to 6 h can be approximated by $P(U)+P(V) \propto f^{-7/3}$. Since power is proportional to the square of amplitude A, we can write $A(U)+A(V) \propto f^{-7/6}$. Now, assuming these periodicities are attributable to traveling disturbances, the spatial equivalent becomes $A(U) \propto n^{-7/6} \cos(n\, x/L)$, for the U component. Assuming the amplitude of the divergent portion of U (U') is proportional to U, we then compute one component of divergence as

27. Fiedler, F., and Panofsky, H.A. (1970) Atmospheric scale and spectral gaps, Bull. Am. Meteorol. Soc. 51:1114-1119.

$\partial U'/\partial x \propto n \cdot n^{-7/6} \sin(n\, x/L)$. To a first approximation we can say that the moisture convergence is proportional to the rainfall rate (for steady state) and the moisture convergence amplitude would be given by $A(-Q \nabla \cdot \mathbb{V}) \propto n^{-1/6}$. Thus, we estimate the power of the rainfall rate to be $P(est.)(R) \propto f^{-1/3}$, which while not exactly the $f^{-2/3}$ found in Figure 4c is close. Hess and Clarke[25] used hourly balloon releases from a 60-km array to compute the spectrum of vertical velocity through horizontal divergence, as well as the wind spectrum. They found $P(U)+P(V) \propto f^{2.6}$ and using the previous arguments, we would expect the power of the divergence to be estimated by $P(est.)(\nabla \cdot \mathbb{V}) \propto f^{-0.6}$; their measurement showed $P(\nabla \cdot \mathbb{V}) \propto f^{-1.0}$, again, quite close. Thus, we should not be surprised that the slopes of the power spectra for wind and rainfall rate (or divergence) should be so dissimilar. An interesting point is that we see the slope for the rainfall rate continuing to periodicities much shorter than 6 h, at which the power of interacting wind eddies seems to get lost in the intermediate turbulence. This suggests that the vertically organized disturbances of perhaps 10 km depth continue to interact to smaller and smaller scales; they may be responsible for small areas of intense precipitation often found in developing storm systems. At periodicities of less than 6 h, the wind spectrum power curve might have an average slope of -1, and if previous arguments were used, we would estimate the rainfall-rate power spectrum slope $f^{1.0}$ instead of the observed $f^{-2/3}$. This leads to the conclusion that the disturbances in the wind field for the intermediate range of 6 h to 10 min are not deep enough to produce significant precipitation, which would be consistent with the idea that they are related to boundary layer turbulence of 1 to 2 km depth. Under very moist conditions, such as near warm fronts, even shallow overturning can produce drizzle or light rain, as well as significantly lowering visibility.

7. DISCUSSION

As previously noted, short-range forecasts are not very accurate in predicting changing weather conditions. Analyses of power spectra uncovered a number of factors that cause difficulty when one attempts to make short-range forecasts, severely limiting accuracy. Prospects for overcoming the difficulties are related to five of these factors.

7.1 Emphasis on "Sensible" Weather Elements

It is rather unfortunate that sensible weather elements are so important to aviation and military interests. Cloudiness, visibility, and rainfall rate all have considerable spectral power in periods shorter than 24 h, producing rapid changes over periods of several hours. Small errors in forecasting the phase ("timing" errors) lead to serious errors in spot forecasts of these elements. In short, these happen to be very challenging parameters to forecast, and most forecasters would be more confident giving out forecasts of temperature, wind, and, perhaps, time-averaged cloudiness and precipitation. However, demands for spot forecasts of sensible weather elements from aviation and other military interests are more apt to increase rather than decrease in the foreseeable future, due to the use of high-technology equipment.

7.2 High Frequency Variance

The spectral data indicate that when making 2 to 8 h forecasts, one should concentrate on those disturbances with periodicities of about 8 to 32 h. If these variations are due to disturbances traveling with a typical "synoptic" speed of 25 knots, the scale size would be about 200 to 800 nm, with an "active" portion about 100 to 400 nm. The data also indicated that the observations used to identify and track these mesoscale disturbances contain a considerable amount of signal from higher frequencies. This high frequency variance is, for this purpose, unwanted noise, in that the observations are not frequent enough to define clearly and track the associated disturbances. Surface wind observations are a good example, as they represent only a 1-min mean (a mean that is not "extreme" relative to other data during a 5-min period). The meteorologist would really prefer a 30- or 60-min vector average, together with some measure of variability. Presently, the best we can do would be to average two or three consecutive wind reports. Rainfall rate is even more of a problem. Local observations comprise a subjective estimate of "none", "light", "moderate", or "heavy" precipitation rate during an observation period of a few seconds to a few minutes; normally once an hour. Rainfall rate is also estimated from radar reflectivity, with coarse 25-mile resolution grid-point data transmitted every hour (manually digitized radar, MDR). The present procedure of coding only a maximum value for the MDR grid is far from ideal, since it provides more information about the variability than about the mean. To a lesser degree of accuracy, rainfall rate can be estimated from satellite imagery, representing a few millisecond snapshot normally every half-hour from a geosynchronous satellite. Considering the amount of high-frequency variability in rainfall rate, one would have to work with time averages of over an hour or more (and also the variance), to filter out high-frequency "noise". Radar and satellite imagery data often have more spatial resolution than needed to track 100 to 400 mile patterns, and spatial smoothing might help to reduce some high-frequency noise. However, this would not work for stationary patterns varying in time at rapid rates.

7.3 Operational Numerical Prediction Models

Developments in operational numerical prediction models have revolutionized forecasting for periods of 24 h and more during the past decade, but these models have done little to assist forecasts of 0 to 12 h. In fact, part of the improved NWP capability at long range has come through initialization procedures that filter out the very disturbances that are important to short-range forecasting, perhaps to a small extent making the situation worse. Over the next 5 years, new and more powerful computers will become available to operational NWP modelers, but at this point we do not know whether the increased power will be used for more complete physics or for better spatial resolution. The short-range forecaster would like to see resolution improved at least to the point where periodicities up to 12 h can be forecast by the models. Such an improvement would greatly benefit the 4- to 8-h forecasts of all elements (with exception of rainfall rate), particularly through realistic predictions of diurnal variations within the boundary layer. However, a factor of 2 improvement in resolution is expensive, requiring 8 times the storage for grid information and 16 times as many computations, compared to the present LFM model. Also, one can argue that much of the diurnal variation is recaptured when the Model-Output-Statistics (MOS) routines use time-of-day among the predictors in making an objective local forecast. In all likelihood, some of the added power of the oncoming new computers will be used for improved spatial resolution, but short-range forecasters should make a good case for their needs.

7.4 Obsolete Frontal Theory

Many of the present-day meteorologists were brought up under the concept that surface fronts (the primary mesoscale disturbance) were necessary for cyclogenesis and were intimately involved in cyclone development through the occlusion process. In the 1950's, the theory of baroclinic instability indicated that only deep layers of thermal gradients were necessary; first (or zeroth) order discontinuities were not necessary. Then came the baroclinic and PE forecast models that successfully forecasted cyclone development without any obvious fronts or other mesoscale patterns, in either initial or forecast fields. The forecaster now knows of no good reason why fronts and other small-scale disturbances should exist; he can only rely on experience and instinct as guides in their analysis and prediction. The concept of wave interaction is probably the best explanation for the small-scale, stable disturbances, and careful inspection of upper-level charts often shows small temperature or vorticity features similar in structure to the larger unstable waves. The accompanying precipitation and cloud patterns are more pronounced. Obviously, they should be tracked and forecast. Perhaps the simplest explanation for the sharp surface cold front is that it develops when cool air advances, forming as a leading edge through large-scale horizontal convergence and boundary layer processes[28] (frictionally retarded isotherms, vertical heat, and momentum flux). Such fronts can be very sharp, often producing cooling rates of 10 F/hour over a 20-min period, and occasionally as great as 60 F/hour over 10 min.[29] These fronts occur not only with baroclinic deepening, but also with smaller, stable waves, with seabreezes, and with thunderstorm surface outflow. Until new and better texts come out in the future, the forecaster is pretty much on his own with respect to analysis and forecasting of small-scale disturbances.

7.5 Cloud Pattern Formation

Another tacit assumption of the meteorologists is that cloud patterns are formed by organized patterns of rising motion in a moist air mass. A cloud would appear when a parcel of air was lifted to the point where saturation occurred, conserving mixing ratio and potential temperature up to that point. However, the spectra of cloud reflectivity and rainfall rate were very different. The rainfall rate spectrum was consistent with what would be expected from divergence and vertical motions of disturbances associated with wave interactions. Are there mechanisms associated with mesoscale cloud patterns other than lifting? Certainly we often see extensive patterns of low clouds behind a baroclinic wave, in an area of large-scale subsidence. These clouds can be attributed to the vertical convergence of moisture due to convection within the boundary layer--the spreading out of fair weather cumuli to form a layer. Altocumulus clouds and cirriform clouds also have fine-scale structures, and it is possible that turbulent processes may be important in their formation as well. In Table 2, we note that the subjective forecast experiments based on 10 cases did much better at cloud forecasting than did the routine forecasts. In the former case, the clouds were predominantly the deep cloud systems associated with precipitation, whereas the latter study took all clouds as they came. The deep cloud systems would likely be more closely associated with mesoscale vertical motion systems and move more systematically than the layered clouds. Certainly, one might try separating areas of deep clouds from areas of relatively shallow low clouds, and use different forecast techniques for the two. In this separation, an overlay of radar and satellite data would be useful.

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28. Sanders, F. (1967) Frontal Structure and the Dynamics of Frontogenesis, Final Report NSF Grant GP-1508.

29. Keyser, D., and Anthes, R. (1982) The influence of planetary boundary layer physics on frontal structure in the Hoskins-Bretherton Horizontal shear model, J. Atmos. Sci. 39:1783-1802.

In the preceding discussion are some indications of steps to improve short-range forecasting. In general, the ideas will not be easy to implement, requiring considerable data processing in a short time before current data become obsolete. Computer assistance is certainly needed. Theory is still a long way from catching up with the short-range forecast problems, so a good case can be made for interactive graphics systems that can utilize the experience and flexibility of human input. Interactive graphics systems, as well as computers for very-high resolution models, are not cheap and hardly could be justified if needed only a small percentage of the time; herein lies a problem. The spectral data present the amplitude-squared for many different frequencies, without indicating how the disturbances are distributed over long time periods. For example, there are significant diurnal temperature and wind variations nearly every day, and usually one or two major cyclones passing through North America every week during the cooler half year. However, disturbances with an 8 to 32 h periodicity (prime importance to short-range forecasting) may occur only once every few days, but with much stronger power than indicated by the spectra averaged over "quiescent" periods as well. Experience indicates this may well be the case. Thus the life of the forecaster may be one of short periods of intense effort and long periods of boredom. Could interactive graphics systems be justified if really needed only 25 percent of the time? A practical solution is the use of quiet periods for training, simulating cases from recorded data (including "false alarms"), which would sharpen skills and make it easier to keep up with changing seasons. Another approach would be the use of teams of forecasters in a central, assisted by a "floating" high-resolution model, that would follow a given storm system and make special forecasts for stations affected by the storm.

At several points in this report, there has been mention of stationary patterns, which may vary with time. These patterns are likely to be present in all spectra, spatial or temporal, usually to an unknown degree. With sufficient data and a more complex analysis scheme, the stationary patterns, even time-varying ones, can be diagnosed. For example, Willson[26] has performed such as analysis for large-scale patterns at mid-troposphere levels. Small-scale stationary patterns are known to exist in fields of low clouds and surface wind, but their relative contribution to the total variance is not known. This presents an important problem, as stationary patterns can be a pitfall to the forecaster. Without other guidance, a synoptic meteorologist is likely to make short-range forecasts by "advecting" weather patterns using some low-level wind field. The extent to which forecasters used advection in the forecasts summarized in Table 2 is not known, but it is likely that they tried, and if so, they were obviously not very successful. A more direct experiment using advection is described in Appendix A. In brief, the advection forecast scores were worse than persistence out to three hours, and worse than the MOS forecasts at 3 and 9 h. A factor that definitely lowered the advection scores was that the stationary and moving patterns were all advected by the model, mixing another form of "noise" in with the signal. A fair degree of sophistication will be required to avoid moving the stationary patterns, particularly the time-varying ones, and perhaps local changes-with-time, and the motion of change fields will prove useful.

8. CONCLUSIONS

The present-day short-range forecaster in the field faces some challenging problems, many of which come into focus when examining the power spectra of the weather elements being forecast. The weather elements important to aviation are inherently difficult to forecast, due to small time and space scales. The data used by the forecaster contain considerable high-frequency noise. The numerical prediction modelers have largely ignored the disturbances of scales important in 2- to 8-h forecasts. There are presently no good theories or models to describe the development and motion of mesoscale disturbances. Moreover, turbulent motions may play a larger role in cloud formation and maintenance than indicated by textbooks.

There are some approaches that should be explored in developing more effective short-range forecast techniques: (1) operational PE models with better than 100-km resolution are needed; (2) time-averaged (2 or 3 h) data should be tried on mesoscale synoptic charts or CRT analyses; (3) temporal and spatial smoothing of geostationary satellite imagery should be performed; (4) separate routines should be developed to forecast vertically deep and shallow cloud formations.

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Appendix A

Test of Short-Range Forecasting Using Simple Advection

Operational numerical prediction models are gradually moving towards higher spatial resolution. However, for the operational meteorologist these models are still a long way from providing accurate guidance on sudden weather changes over short time periods. One interim solution is to assume that the fine-scale structures in the surface weather patterns are moving with an upper-level flow. Thus, to forecast the future patterns, one would essentially use the old-fashioned "steering" concept, quite successfully used for cyclones and anticyclones.

A recently-added trajectory software routine provided a fairly simple means to test this concept on the AFGL Man-Computer-Interactive-Data Access-System (McIDAS). To use this routine, one starts with an objective analysis technique that uses radiosonde wind information to specify the u and v components throughout an array of gridpoints. For this test, an 18 × 35 array was used, at one-degree latitude-longitude intersections, usually with the northwest corner at 49 N and 92 W. Two steering fields were tested, the 700-mb wind (which performed well in a satellite prediction test - Muench[A1]) and a vertically integrated 850- to 300-mb wind. Given the fields of u and v, one option of the trajectory routine will make objective forecasts for a specified location by assuming that a specified parameter is conservative and can be advected by the "steering" current. To use

A1. Muench, H.S. (1981) Short-Range Forecasting of Cloudiness and Precipitation Through Extrapolation of GOES Imagery, AFGL-TR-81-0218, AD A108678.

this option, one must request an objective analysis of some weather parameter (reported on the "hourly" aviation circuits). This parameter need not be observed at the same time as the steering current, as we normally have 2 to 3 h of fresher data by the time radiosonde information is ready for analysis.

When the necessary analyzed grid fields are stored in McIDAS, one then specifies the number of hours of forecast and the three-letter station identification for the forecast station, and in the matter of a minute or so, the forecasts are displayed (or printed). For example, the following commands produce a 15-h forecast, in 1-h increments, using the 1200 GMT 700-mb wind and 1500 GMT surface dew point data.

SX Z *49092 32068 NON (abbreviates latitude-longitude data by "Z")

KY STR 700 161200 #Z (computes 700 mb u and v in grid)

KZ TD 161500 #Z (computes surface dew point at gridpoints, 1500 GMT)

PF 1 3 15 BOS (uses u from grid 1 and v from grid 2 to compute forecasts by advecting information from grid 3--dew point, in 1-h steps to 15 h, for station BOS)

A three-week test of this routine was run from 15 October 1981 through 6 November 1981. Five parameters were forecast; cloud amount, the u-component, the v-component (surface winds), visibility, and dew point. Temperatures were not forecast, as the diurnal variations cannot be forecast by this system. Three stations were selected: Boston, Mass., Burlington, Vt., and Atlantic City, N.J., all with quite different local terrain. For comparison purposes, model-output-statistics (MOS) forecasts were obtained for these three stations through the Air Force COMEDS terminal at AFGL. The primary standard of comparison for short-range forecasts is a "persistence" forecast: How well do these techniques forecast change?

The forecasts were made from 0000 to 0300 GMT and 1200 to 1500 GMT data, on weekdays, and a set of forecasts for the three stations took about 30 min of interactive time to enter commands, wait for execution, and enter the forecasts on forms.

The forecast parameters were not all in identical form, so, for ease in verification and comparison, cloud amount and visibility were converted to categories, and the "error" of a forecast was the number of categories from correct forecast. Wind forecasts were scored on the basis of the magnitude of the vector error, and dew point error was simply the scalar difference between the forecast and observed (dew point forecasts are not included in the GWC format for MOS forecasts).

The resulting scores representing some 70 forecasts at 6 time intervals are shown graphically in Figures A1 through A4. These scores were converted to

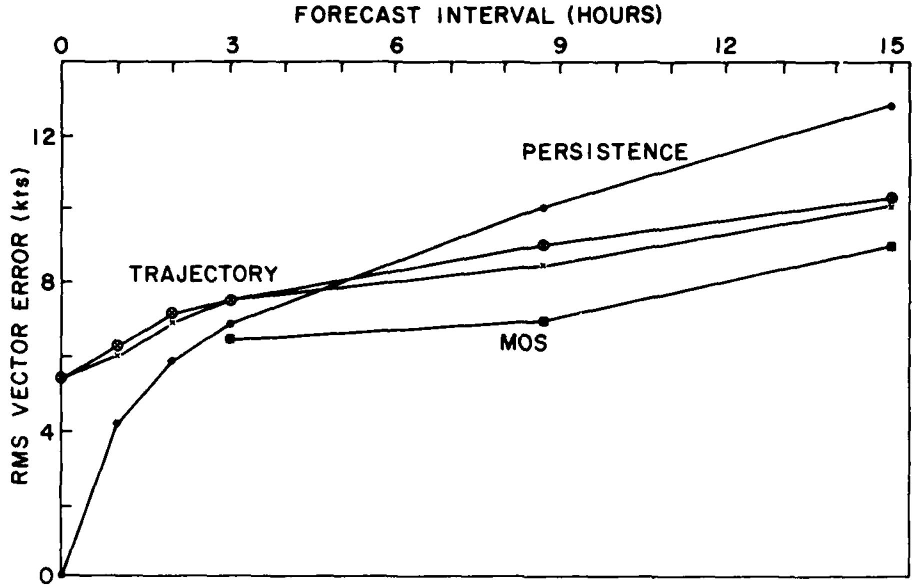

Figure A1. Forecast Scores for Short-range Forecasts of Surface Wind

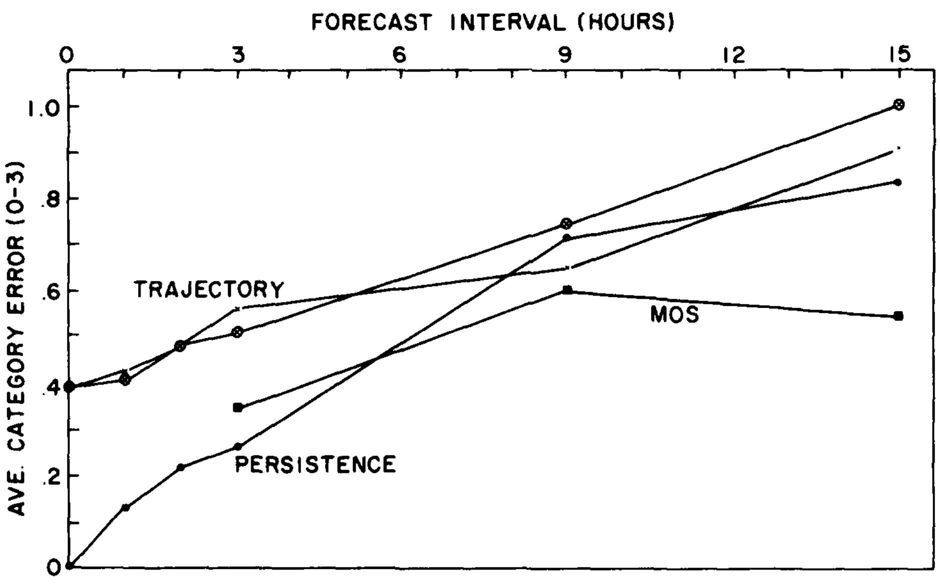

Figure A2. Forecast Scores for Short-range Forecasts of Total Cloud Amount

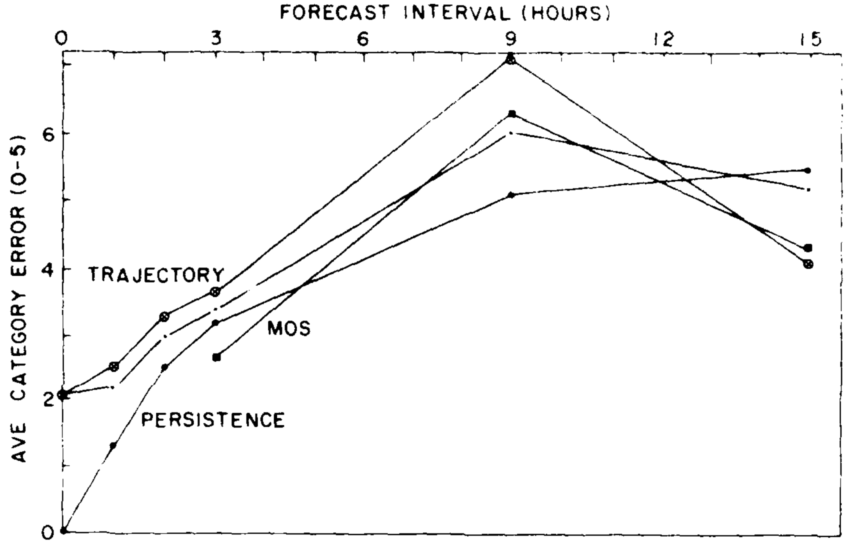

Figure A3. Forecast Scores for Short-range Forecasts of Visibility

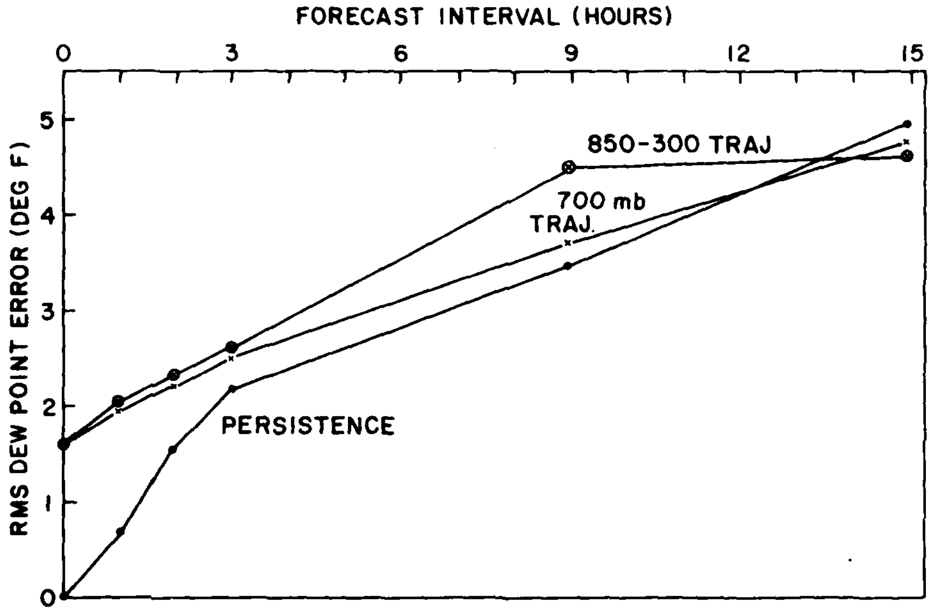

Figure A4. Forecast Scores for Short-range Forecasts of Dew Point skill-scores with respect to persistence and listed in Table A1. Looking at either the figures or the table, one quickly sees that the trajectory (advection) forecasts did not score too well with respect to persistence or MOS. Part of the problem was in the interpolation, as can be seen from the errors at time zero. A simple fix for this problem would be to extract predicted changes from the forecasts and add these changes to the observed initial condition, but even this fix would only bring the errors to a little worse than persistence at 1 to 3 h, with little effect on the 9- and 15-h scores. It is curious that the skill-scores are better for the trajectory forecasts at 9 and 15 h than 1 to 3 h; yet the assumptions of constant steering flow and conservativeness of the forecast parameters should favor more skill in the shorter range forecasts. In retrospect, we should have been concerned about the coarseness of the grid -- one degree-by-one degree was the highest resolution available at the time (1/2 degree-by-1/2 degree is now available) and the station spacing really justified much finer resolution. However, a coarse resolution might hinder improvement over persistence because some mesoscale disturbances were missed; it would not account for scores systematically worse than persistence in the 1- to 3-h period. The simplest explanation is that much of the mesoscale spatial variation we see in high-resolution maps is due to stationary patterns related to orography, and when we try to advect these patterns in routine forecasts, we do more damage to the forecast scores than good.

Table A1. Skill-Scores Relative to Persistence

	Time Interval (h)				
	1	2	3	9	15
700mb Trajectory	-0.60	-0.18	-0.09	+0.15	+0.21
850-300mb Trajectory	-0.67	-0.20	-0.09	+0.12	+0.20
MOS	X	X	+0.05	+0.31	+0.30
700mb Trajectory	-2.23	-1.19	-1.16	+0.09	-0.09
850-300mb Trajectory	-2.12	-1.19	-0.94	-0.04	-0.20
MOS	X	X	-0.41	+0.16	+0.46
700mb Trajectory	-0.67	-0.18	-0.04	-0.18	+0.06
850-300mb Trajectory	-0.89	-0.30	-0.13	-0.41	+0.25
MOS	X	X	+0.17	-0.23	+0.21
700mb Trajectory	-1.74	-0.41	-0.16	-0.08	+0.03
850-300mb Trajectory	-1.90	-0.48	-0.23	-0.31	+0.06